POSTURAL CONTROL VARIATION IN THE SINGLE LEG ANTERIOR REACH

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Undergraduate Thesis

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Abstract

The single leg anterior reach (SLAR) is often used to assess dynamic postural control. However, the SLAR has yet to undergo a balance plate assessment of postural control that may yield information on the movement coordination strategy utilized during the SLAR. The goal of this study is to examine the effect of different postural control strategies utilized to complete SLAR. Subjects included 31 male professional lacrosse athletes (26.7±2.87 years, 1.82±0.07 m, and 89.7±11.1 kg) and 15 NCAA Division 1 female volleyball athletes (19.4±1.15 years, 1.82±0.08 m, and 75.6±7.6 kg) who performed balance plate instrumented SLAR measurements. Center of pressure (CoP) position data were collected during each trial via a portable balance plate and the CoP excursion (CoPE) for each trial was calculated. CoPE was dichotomized into high (greater movement variability) and low (lower movement variability). Between group t-tests were performed between high vs. low CoPE groups to assess normalized reach distance between movement strategy with an alpha level set at .05. Reach distance was significantly higher in those with higher CoPE in the frontal plane (Left: 62.22±3.90 cm high excursion (HE), 60.96±4.07 cm low excursion (LE), Right: 62.32±3.87 cm HE, 60.86±4.07 cm LE) and total CoPE for the right leg (61.92±5.46 cm for HE and 59.87±4.27 cm for LE). Reach distance was greater in those with higher CoPE in the sagittal plane (Left: 63.45±4.27 cm HE, 59.73±2.68 cm LE, Right: 62.39±5.56 cm HE, 59.40±3.82 cm LE) and total CoPE for the left leg (62.32±3.87 cm for HE and 60.86±4.07 cm for LE). Increased frontal plane movement variability during a sagittal reach SLAR task resulted in greater reach performance. These findings may have clinical implications for individuals demonstrating a lack of movement variability in the frontal plane resulting in lower sagittal plane reach distances. Improvements to frontal plane movement variability strategies may result in increased dynamic postural control.

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Chapter 1

1.1 Neuromuscular Control

1.1.1 Definition

Neuromuscular control is a foundational component to human movement playing a critical role in joint stability, motor control, and function. Neuromuscular control is defined as the interaction between the nervous and musculoskeletal systems to produce a desired effect or response to a stimulus [24]. Proprioceptively mediated exercises or exercises that focus on developing optimal balance, necessitate an appreciation of the central nervous system's influence on neuromuscular control[8]. This afferent feedback is received by the central nervous system (CNS) and is used to modulate efferent responses at the spinal and supraspinal levels[8]. These efferent responses are identified as neuromuscular control and involve transforming neural information into physical energy[54,55,87]. Efferent or motor nerves carry impulses away from the CNS to effectors, e.g. muscles or glands. Afferent or sensory neurons carry impulses from receptors or sense organs towards the CNS.

1.1.2 Components

Components of neuromuscular control include proprioception, muscle strength, muscle reaction time, and postural control[75]. Postural control and balance are key factors in the neuromuscular control profile of the lower extremity. According to Lephart and Henry[54], neuromuscular control can be organized into a paradigm which breaks down the inputs and outputs of motor control. Inputs of the CNS include somatosensory, visual, and vestibular afferent signals. The CNS divides into three levels of motor control – spinal reflexes, cognitive programming, and brain stem activity, which involves balance. The output or result of this process is efferent impulses sent to the muscles which create movement in the musculoskeletal system[54].

1.1.3 Assessment

Several methods to quantify neuromuscular control exist and are capable of assessing different aspects of the neuromuscular functional profile. One of these methods includes electromyography (EMG) to detect muscle recruitment patterns during dynamic tasks. Another such method is three-dimensional kinematics which uses passive markers to trace positions of body segments in order to calculate joint angles or segment accelerations. Strength output is used to measure power and endurance. These aspects are not the focus of this investigation, but play a role as no aspect of neuromuscular control should be interpreted without consideration of the entire profile.

1.1.4 Neuromuscular Control Intervention

Neuromuscular training programs that incorporate balance, strength, plyometric, agility, and sport-specific exercises often targeted to optimize performance, prevent injury, and improve rehabilitation outcomes [99]. Restoring dynamic stability should encompass the neurosensory subsystems (somatosensory, visual, and vestibular) and the levels of neuromuscular control (spinal reflexes, cognitive programming, and brain stem activity)[54]. To determine the level of postural control in the neuromuscular functional profile in various populations a variety of tools from the simple clinical observation to highly sophisticated force plate technology exists.

One of the main objectives of proprioception and neuromuscular control training are to enhance sensation of the injured joint by retraining altered afferent pathways and to recruit secondary somatosensory, visual, and vestibular pathways[54,55]. According to Hertel and Denegar[41], the rehabilitation process to restore neuromuscular control after injury follows a system of controlling volitional muscle contractions, restoring reflex responses to perturbations, and then restoring normal pattern generated movements.

1.2 Balance

1.2.1 Definition

Balance, simply defined, is the attempt to counteract unstable equilibrium [47] or the ability of the body to maintain the center of gravity within the limits of stability as determined by the base of support[46]. Balance is a generic term describing the dynamics of body posture to prevent falling[98]. By nature, humans are unstable structures that are constantly exposed to perturbations. Individuals use visual, vestibular, and somatosensory information to plan and execute motor commands in order to retain balance[42]. A constant state of unsteadiness is maintained through human's innate intrinsic support system, specifically the musculoskeletal and neuromuscular systems. The multifactoral nature of balance and postural control likely contribute to the inability or difficulty in developing a universal definition or measure. Postural control is an essential component to assess the effectiveness of interventions for improving balance [16].

1.3 Postural Control

1.3.1 Definition and Categories

Postural control is defined as and individual's range or spectrum of capability to maintain balance above a base of support [18]. Key fundamentals for the postural control system are sensory information from somatosensory, vestibular, and visual systems[45]. The complex interaction of the musculoskeletal and neural systems allow for the body to control its position in space for stability and orientation.

Postural control can be categorized into two components – static and dynamic. Specific definitions of aspects of postural control allow researchers and clinicians to classify and identify balance strategies more distinctly.

1.3.2 Static Postural Control

Static postural control is the attempt to maintain a position with minimal movement [52] or balance on a stable surface without intentionally moving [3]. Maintaining balance during a static task is essential for overall postural control and balance. Common assessments for static postural control include double-leg stance, single-leg stance, and the Balance Error Scoring System (BESS). The BESS measures an athlete's postural stability through a clinical-assessment battery and is scored by counting the errors the athlete commits during the tests[76]. The BESS is often used to assess athletes immediately after suffering a mild head injury or concussion to quickly determine the effects on the postural control system. Along with individuals who sustain head injuries, the elderly are another population who utilize static postural control assessments to determine risk of injury or risk of falling. Falling is a common occurrence in the elderly and can be assessed using static postural control methods to determine impairments in balance.

1.3.3 Dynamic Postural Control

Dynamic postural control is the ability to maintain a stable base of support while completing a prescribed movement [32] or complete a balance task that requires performing some movement or task [3]. Assessments used most often for dynamic postural control include jump-landing, gait, and the Star Excursion Balance Test (SEBT). Dynamic tasks are often used to test the postural control of athletes with functional or mechanical ankle instability. The SEBT is a useful assessment for dynamic postural control of individuals with ankle instability due to the heightened challenge imposed on the ankle joint during the dynamic task. The dynamic postural control component of the SEBT is thought to challenge the lower extremity's neuromuscular system.

1.3.4 Implications for Athletes – Postural Control Risk Identification

The need for postural control, both static and dynamic components, is readily apparent in the sport setting due to the constant requirement of athletes to maintain balance during high speed maneuvers for optimal performance [78]. Assessing postural control has been implemented in the sports medicine field to quantify a key aspect of neuromuscular control in athletes, identify athletes at higher risk for injury, improve prevention strategies, and use as a progressive marker for rehabilitation from injury[79]. Although there are several tests that have been developed in order to assess static and dynamic postural control, it is unknown if they have the capability to challenge the limits of postural control of healthy athletes. The current climate of rising healthcare cost and demand for outcomes research heighten the need for sensitive objective measures of postural control in order to identify rehabilitative markers for various pathologies and assist with return to play decisions.

1.3.5 Implications for Athletes - Pathologies

Instrumented assessment of postural control has been used to quantify functional impairments in patients with various orthopaedic injuries. Postural control aspects of neuromuscular control objectively quantify deficits in balance for anterior cruciate ligament [38,59,84,85], ankle [3,20,28,40,71,92,93], hip [52], and lumbosacral[2,57,58,65] pain and injury risk as well as development of chronic ankle instability [11,17].

Knee injuries, including ACL and PCL tears, are other injuries that benefit from postural control assessment[8,38,43,59,61,70,84,87,88]. Athletes who display greater proprioceptive acuity, or greater postural control and balance, demonstrate greater knee function[8]. Compared to healthy individuals, those with an ACL injury display a significant displacement of the CoP in the anterior direction during stabilometric measurements[88].

Athletes with functional ankle instability have shown patterns of poor balance performance or limited postural control through single-leg balance tasks which has been said to be caused by disrupted sensorimotor pathways, indicating a diminished postural reflex response in the presence of mechanical ankle instability[25].

Head traumas, specifically sports-induced concussions, are a common injury assessed by researchers and clinicians by examining changes in postural control through static and dynamic tasks. Many studies have shown diminished or compromised postural control or balance of athletes following a concussion or traumatic brain injury as much as 72 hours post-injury[9,10,13,14,34,36,74,83,86].

Individuals with low back pain have also displayed reduced postural control during static balance tasks, which greatly affects overall balance capabilities[2,37,57,58,65,82].

Knee injuries, ankle instabilities, head traumas, and low back pain are just a few pathologies that are used in assessing postural control measures to identify changes in balance compared to healthy individuals. Further understanding postural control deficiencies caused by injuries will allow researchers and clinicians to better identify and rehabilitate these pathologies.

1.3.6 Implications for Athletes – Exercise Interventions

For injured athletes, return of optimal postural control is an important rehabilitation goal[15]. Implementing such exercises or tasks as a single-leg stance can assist in identifying athletes with possible neuromuscular or postural control deficits earlier, which could lead to prevention of more serious sports injuries. For athletes that have suffered injuries, a rehabilitation program that includes exercises with the goal of returning to optimal postural control is essential and a key component in the athlete's return to play.

1.4 Postural Control Strategies

1.4.1 Postural Stability Strategy

Postural stability has been defined as an individual's ability to maintain the center of mass over the base of support [70] or the ability to resist perturbations [56]. The postural control stability strategy refers to the ability to maintain the body in equilibrium over the base of support. In order for optimal postural stability to be accomplished, maintaining a desired postural orientation, either at rest or during movement, in response to a disturbance of equilibrium generated from internal or external sources must be accomplished [15].

The control of postural stability can be viewed as a triple-input, single-output system with proprioception, vision, and the vestibular system as the main sources of information on the position of the body in space, and the output of control is the position of the center of pressure within the base of support[7].

Assessing dynamic postural stability is a common method used to quantify deviations in balance from neutral point and can be used as a simplified method to quantify an individual's ability to control movement of the center of mass in a dynamic task[70].

It has been generally assumed that individuals, especially athletes, who demonstrate normal stability, have a healthy, well-developed postural control system. Athletes with greater stability are associated with greater control of postural sway about the central equilibrium point, described as fewer excursions in movement [15].

1.4.2 Postural Variability Strategy

Postural control variability strategy is characterized by greater deviations in movement, planning, and execution, or the "noise" produced, during postural control tasks[18]. Variability has been accepted as unavoidable and a normal, functional component of balance that is associated with motor redundancy[18]. Even though variability is inevitable it can be reduced or maintained through training and practice with postural control exercises and tasks[18].

1.4.3 Postural Control Strategy Integration

Postural stability and variability are both key aspects to maintaining optimal balance. Neither postural control strategy has proven to be more beneficial than the other, but identifying or determining strengths of each strategy is essential for specific balance training programs and rehabilitation.

Chapter 2

2.1 Clinical Measures

Three levels of clinical measures exist which have developed over time from basic, qualitative methods to intricate, more quantitative methods. The primary level includes such instruments and methods as tape measures, e.g. measure maximum distance for single-leg anterior reach or a broad jump, goniometers, e.g. measure maximum range of motion angle of joints, and the Balance Error Scoring System, which uses error counts to assess static postural control of healthy and injured individuals. Secondary level incorporates balance plates and jump plates. Both balance and jump plates are specialized forms of force plates which measure the vertical force and two moments which can be used to compute the center of pressure position. Finally, the tertiary level of clinical measures utilizes more advanced technology for assessment, such as force plates, which measure three force components along the x, y, and z axes and three moment components about the x, y, and z axes for a total of six outputs, as well as kinematics, which utilize passive markers to identify positions of specified segments during dynamic tasks.

2.2 Force Plates

2.2.1 Definition

Force plates are devices or instruments used for measuring force, center of pressure position, and moments developed during a specified static or dynamic task.

2.2.2 Types

Piezoelectric force plates use crystal or ceramic sensors to detect through compressive and tensile deformation. These force plates are highly sensitive to dynamic force changes, e.g. jump task, but are a poor measurement of static force, e.g. static postural sway task.

Strain gauge force plates contain conductors that change thickness with compression (thicker) and tension (thinner). The change in thickness denotes a change in resistance – compression correlates to decreased resistance and tension correlates to increased resistance. Strain gauge force plates are more commonly used for static force measurement than dynamic force.

2.2.3 Variables Measured

Force plates measure three components during static and dynamic tasks – ground reaction forces, center of pressure position, and moments.

The forces measured are known as the ground reaction forces (GRF) and are collected in the vertical, anterior-posterior, and medial-lateral directions, which are usually represented in the x-y-z coordinate system. The GRFs are often observed at the center of pressure to assess postural control and balance measures. Two components of GRFs have been identified. Vertical GRF accounts for the acceleration of the body's center of mass in the vertical direction. Horizontal GRF is the frictional force or force parallel with the surface.

Center of pressure is the point of application of the GRF on the force plate. The position of the center of pressure can be computed from the moment caused by the GRF about the true origin. The moments measured from the force plate are equal to the moments caused by the GRF about the true origin plus the free torque vector.

2.2.4 Balance Assessment

Quantifying postural control has been more recently accomplished using technology and instruments such as force plates or force platforms. Force plates are used regularly in the clinical[33] and research[27,66] setting to assess postural control. Variations in GRFs have been determined as one of the best predictors of postural stability during static tasks, e.g. single-leg stance[80], showing that the components of the GRF with the least variation during a task might be an indicator of optimal postural stability[81]. Brown et al[11] found that individuals with mechanical ankle instability (MAI) demonstrated more variability in the anterior-posterior GRF than those with functional ankle instability. This increased variability may potentially be a chronic or acute orthopedic injury risk factor for individuals[11].

2.3 Center of Pressure

2.3.1 Definition

Center of pressure is the point of application of the ground reaction force on a force plate or the point at which the pressure of the body over the soles of the feet would be if it were concentrated in one spot[82].

2.3.2 Balance Assessment

One of the most commonly used variables to test postural control through the use of force plates is center of pressure (CoP). CoP can provide insight into how the CNS controls movement of the center of mass as the CoP tracks and controls the movements of the center of mass within the base of support during static postural control tasks[1]. Several variables have been derived from CoP movements in order to quantify postural control and balance, e.g. excursion length, velocity, area, amplitudes in the anterior-posterior and medial-lateral directions, or displacement[21,26,35,53,62–64,69,82].

2.3.3 Excursion Length

Total excursion is the length of the path traveled by the CoP throughout a specific task. Researchers suggest that an increase in total excursion represents a decreased ability by the postural control system to maintain balance[23,44,51,94]. Ruhe et al[82] verified CoP total excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy individuals. They found that non-specific low back pain patients displayed greater postural instability and increased CoP mean displacement, significant in the anterior-posterior direction, as compared to healthy individuals[82]. Traditionally, CoP excursion has been used to identify individuals with injury conditions, but with limited prospective evidence the conditional use of mostly static posture makes higher CoP excursion an inconclusive injury risk factor.

2.3.4 Velocity

The total distance traveled by the CoP over time represents CoP velocity, another common postural control variable used for balance assessment. Several researchers and clinicians[5,6,48,49,60,67,94,95] have used CoP velocity in order to assess changes in the CoP during static and dynamic tasks. It has been determined that CoP velocity inversely correlates to postural control with an increase in velocity indicating a decrease in ability to maintain or control balance[4–6,19,22,23,90]. Hale et al[35] found individuals with chronic ankle instability displayed higher CoP velocity when standing on the involved or injured limb compared to the uninvolved or healthy limb. McGuine et al[63] measured CoP velocity as degrees of postural sway per second with a higher sway velocity indicating an increased postural sway or poor ability to balance. It was determined that preseason measures of balance as quantified by postural sway predicted susceptibility to ankle sprain injury; this was supported by the finding that preseason velocities for individuals who sustained ankle sprains were significantly higher than those who did not sustain an ankle injury[35]. Along with ankle instability, non-specific low back pain has been used as a means to assess CoP velocity in order to identify injury. Ruhe et al[82] found that patients with non-specific low back pain displayed higher CoP velocities than healthy individuals.

2.3.5 Sway Area

Center of pressure area, or better known as sway area, is the surface contained within the closed curve including all recorded CoP points[73]. An increase in sway area is a reflection of postural instability[1]. Compared to healthy individuals, patients with non-specific low back pain exhibit greater sway area[82], indicating poor postural control.

2.4 Single Leg Balance Assessments

2.4.1 Balance Assessment Implications

Single leg balance tests, both static and dynamic, have been used by clinicians and researchers to measure postural stability or balance[1,4,12,17,23,31,32,50,63,72,96]. Single leg balance assessments are an effective, postural control methodology to identify and rehabilitate injuries, especially to lower extremity injuries. The single leg stance allows for the assessment of balance under conditions that introduce additional challenges to the postural control system and reduces the base of support, which requires the postural control system to make more adjustments in order to maintain balance[69].

Trojian and McKeag[91] found an association between a positive single-leg balance test and ankle sprain. In athletes with a positive single-leg balance test, not taping the ankle imposed an increased risk of sprain and hence the single-leg balance test was reported to be a valid test for predicting ankle sprains[91].

2.4.2 Star Excursion Balance Test

The Star Excursion Balance Test (SEBT) is a dynamic single leg balance assessment that requires individuals to perform eight maximum single-leg reaches in a variety of directions. Figure 1 shows the SEBT set-up with the eight directions marked 45° apart from each other and include the following directions: anterior, posterior, medial, lateral, posterolateral, posteromedial, anterolateral, and anteromedial[31]. One foot is placed in the middle of the star pattern and then the subject is instructed to reach as far as possible, sequentially (either clockwise or counter clockwise), in all eight directions. Because of the significant correlation between SEBT and leg length ($.02 \leq r2 \leq .23$) in a majority of the directions, excursion values should be normalized to leg length, measured from the ASIS to the medial malleolus[32]. The SEBT has been proven to be a valid test used to assess dynamic postural control deficits and outcomes in lower extremity [17,31,32,72,89], but quantification of postural control strategy during this task is generally not understood.

To decrease the effect of learning, Kinzey and Armstrong[50] suggested that subjects be given at least six practice trials before being tested, although Robinson and Gribble[77] suggested reducing the number of practice trials to four.

Individuals with chronic ankle instability (CAI) have been extensively assessed using the SEBT as a method for postural control assessment[17,39,68]. Chen et al[17] found that those with CAI displayed a larger displacement of anterior/posterior CoP trajectory in the anterolateral direction and a smaller displacement of medial/lateral CoP trajectory in the posterior direction than healthy individuals. Their findings helped to identify CAI individuals as having poor dynamic postural control. Hertel et al[39] found that those with CAI showed significant reach deficits in the anteromedial, medial, and posteromedial directions. Olmstead et al[68] found decreased reach distances in CAI individuals while balancing on the injured side compared to the matched side of an uninjured individual and when compared to the individual's own uninjured side. It was also found that the posterior and posteromedial reaches were significantly longer than the reaches in the anterior, anteromedial, and posterolateral reaches of those with CAI[68]

Plisky et al[72] came to several key conclusions to help identify lower extremity injuries in high school male and female basketball players using the SEBT – (1) for all players, an anterior right/left reach distance difference greater than or equal to 4 cm, decreased normalized right anterior reach distance and decreased normalized posteromedial, posterolateral, and composite reach distances bilaterally were significantly associated with lower extremity injury, (2) for girls, an anterior right/left reach distance difference of greater than or equal to 4 cm and decreased normalized anterior, posteromedial, posterolateral, and composite reach distances bilaterally were significantly associated with lower extremity injury, (3) for boys, only an anterior right/left reach distance difference greater than or equal to 4 cm was significantly associated with lower extremity injury, (4) a normalized composite right reach distance of less than or equal to 94.0% was significantly associated with lower extremity injury for all players and for girls, (5) an anterior right/left reach distance difference of 4 cm or more was significantly associated with lower extremity injury for all players and boys, and (6) a decreased normalized right composite reach distance and greater anterior right/left reach distance difference on the SEBT predicted lower extremity injury.

2.4.3 Y Balance Test

The Y Balance Test is an assessment used to measure dynamic postural control based off of maximal reach. The Y Balance Test is categorized into the lower extremity and upper extremity postural control assessments.

The Y Balance Test – Lower Quarter (YBT-LQ) is a modified SEBT only using the anterior, posteromedial, and posterolateral directions to assess maximal reach distance for dynamic postural control (Figure 2)[31].

Gorman et al[30] found no significant interactions or main effects relating the number of sports played by high school athletes for any YBT-LQ score. Male athletes exhibited significantly greater normalized reach distances for the posteromedial, posterolateral, and composite reach while also exhibiting a larger anterior reach difference when compared to female high school athletes[30]. Athletes who participated in multiple sports had similar reach performances on the YBT-LQ when compared to athletes who participated in only one sport[30].

Butler et al[12] found high school soccer players reached a greater distance compared to collegiate and professional soccer players in all directions of the YBT-LQ. Professional soccer players performed greater dynamic balance during the YBT-LQ than the high school soccer players except for their performance in the anterior direction in which high school athletes showed greater dynamic postural control[12].

The Y Balance Test – Upper Quarter (YBT-UQ) is performed for maximal reach distance in the medial, superolateral, and inferolateral directions in relation to the stationary arm. The

YBT-UQ has been proven to be a reliable test and may serve as a good measure in return to sport testing when rehabilitating upper extremity injuries[29,97]. In addition, it was found that there was no difference in YBT-UQ performance between dominant and non-dominant limbs, which helps support using this test as a return to sport assessment[29,97].

2.4.4 Single Leg Anterior Reach

The Single Leg Anterior Reach (SLAR) test, which is the anterior direction of the SEBT, is one example of a dynamic postural control test that has been used to assess athletes' balance capabilities [17,63,72,89]. The SLAR is a unilateral, functional joint-stability task that incorporates a single-leg stance of one leg with a maximum targeted reach of the contra-lateral leg in the anterior direction [89] (Figure 3).

Chapter 3

3.1 Introduction

The single leg anterior reach (SLAR) of the star excursion balance test is often used to assess dynamic postural control. Previous research has shown more significant differences in reach performance between injured and uninjured subjects in the anterior-posterior direction [17,72].

Clinical SLAR has proven to be an effective method to test dynamic postural control in athletes, especially with lower extremity instabilities such as ankle sprains and ACL-reconstructions. However, the SLAR has yet to undergo a force plate or instrumented assessment of postural control that may yield crucial information on the movement coordination strategy utilized during the SLAR.

Measures of SLAR have shown multiple postural control strategies (e.g. stability and variability) through maximal reach distance and CoP assessment. Understanding the underlying postural control strategy for SLAR will improve our mechanistic knowledge of dynamic postural control. This improved assessment sensitivity is hoped to translate to improve injury prediction models.

3.2 Purpose

The goal of this study is to examine the effect of different postural control strategies utilized to complete the SLAR.

3.3 Hypothesis

It is anticipated that this research will indicate athletes with high variability are able to reach further when normalized to leg length than those with high stability.

3.4 Subjects

Before participation, subjects were informed of all possible risks and signed a consent form approved by the Ohio State University Institutional Review Board. Prior to the start of their respective athletic seasons, 31 male professional lacrosse athletes (26.7±2.87 years, 1.82±0.07 m, and 89.7±11.1 kg) and 15 National Collegiate Athletic Association Division I (NCAAI) female volleyball athletes (19.4±1.15 years, 1.82±0.08 m, and 75.6±7.6 kg) were recruited for the study. In order to participate, the athletes had to be free of any lower extremity injury within the last 6 months.

3.5 Equipment and Instrumentation

The SLAR test was instrumented and tested on a triaxial force plate (FP6090-15-2000, Bertec Corporation, Columbus, Ohio). Bertec Digital Acquire™ software collected center of pressure position data from the force plate throughout each trial. Center of pressure excursion was calculated using custom Matlab 7.2 (Mathworks Inc., Natick, USA) coding (Figure 4). Figure 5 shows an example of center of pressure position data plotted in Matlab collected from the Acquire software.

3.6 Procedure

Athletes performed a force plate, instrumented SLAR for this study. The SLAR protocol was used based off of the SEBT methods described by Gribble et al[31]. While maintaining a single-leg stance and keeping hands on hips and the heel of the stance foot flat on the surface, participants were instructed to maximally reach with the contra-lateral limb in the anterior direction, touch the tape measure with the distal part of the foot, and return to starting position. Following protocol, participants performed three practice trials for each reach leg and then performed three recorded or data-collecting trials for each leg. The reach distance, normalized to leg length, was measured in centimeters from the starting point to the farthest point on the measurement line the participant was able to touch. Testing ended if the participant indicated any pain in the lower extremity or wanted to stop testing for any reason.

To control for multiple variables, a second examiner monitored the athlete's performance by making sure the stance heel maintained flat on the ground and hands on the hips throughout the entire trial. If the athlete did not maintain these parameters, the trial was repeated. The primary examiner ran the software to collect CoP positions during the trial.

3.7 Testing Methods

Center of pressure was used to quantify the level of postural control for all subjects. The CoP positions in the x (medial-lateral direction or frontal plane) and y (anterior-posterior direction or sagittal plane) axes were recorded during each trial of the SLAR. Once calculated from position data, CoP excursion in the x and y axes as well as total excursion was averaged for the subject's three recorded trials in the left as well as those in the right leg.

For each trial, maximal reach distance was normalized to the subject's leg length, measured by the distance from anterior superior iliac spine (ASIS) to the apex of the medial malleolus, and presented as a percentage of leg length (%LL)[32]. Maximal reach was recorded as the furthest distance the subject could perform reflected by a slight toe-tap of the reaching leg on the measuring tape. Each subject's reach distances were recorded for both the left and right leg by a second examiner. Reach distance was averaged from the three testing trials completed on both the left and right leg for each subject.

3.8 Statistical Analysis

Statistical analysis was completed using SPSS (version 17; SPSS Inc, Chicago, IL). CoP excursion was calculated for each trial and then dichotomized by 50th percentile of CoP excursion into postural control strategy groups - high CoP excursion (greater movement variability or high variability strategy) and low CoP excursion (lower movement variability or high stability strategy). Between group t-tests were performed between high and low CoP excursion groups for CoP excursion in the x axis (CoPx), y axis (CoPy), and total CoP excursion (CoPtotal) to assess normalized reach distance between postural control strategies with an alpha level set at .05.

3.9 Results

For the left SLAR, CoP excursion was dichotomized at .39 meters (m) in the x axis, .32 m in the y axis, and .555 m for total excursion. For the right SLAR, CoP excursion was dichotomized at .38 meters in the x axis, .314 m in the y axis, and .548 m for total excursion (Table 1).

Reach distance was significantly higher in those with higher CoPE in the frontal plane (Left: 62.22±3.90 cm high excursion (HE), 60.96±4.07 cm low excursion (LE), $p=0.007$; Right: 62.32±3.87 cm HE, 60.86±4.07 cm LE, $p=0.045$) and total CoPE for the right leg (61.92±5.46 cm for HE and 59.87±4.27 cm for LE, $p=0.0173$). Reach distance was greater in those with higher CoPE in the sagittal plane (Left: 63.45±4.27 cm HE, 59.73±2.68 cm LE, $p=0.3$; Right:

62.39±5.56 cm HE, 59.40±3.82 cm LE, 0.822) and total CoPE for the left leg (62.32±3.87 cm for HE and 60.86±4.07 cm for LE, p=0.23). Table 2 shows the results of the dichotomized mean reach distances for left SLAR with the dichotomized CoP excursions. Table 3 shows the results of the dichotomized mean reach distances for the right SLAR with the dichotomized CoP excursions. Figures 4-6 show the left SLAR mean reach distances compared to the low and high CoP excursion for the y axis, x axis, and total excursion respectively. Figures 7-9 show the right SLAR mean reach distances compared to the low and high CoP excursion for the y axis, x axis, and total excursion respectively.

3.10 Discussion

Postural control has commonly been identified as a key indicator of balance abilities and used as an injury risk predictor, but investigation on the types of control strategies has not yet been examined. The primary finding of this study was that subjects with increased CoP frontal plane excursion performed greater single leg anterior reach distances. Increased frontal plane movement variability during a sagittal reach SLAR task resulted in greater reach performance.

The subjects in the low CoP excursion group, or the high stability group, did not have as great of a single leg anterior reach as the high CoP excursion group, or the high variability group. These results could be influenced by several factors, such as lack of lower extremity muscle strength in order to sustain the body while balancing to perform a dynamic task, limited ankle dorsiflexion for optimal reach performance, or decreased knee and hip flexion in order to lower the center of mass for further anterior reach.

Subjects in the high CoP excursion group, or the high variability group, performed significantly greater single leg anterior reach, especially in the frontal plane. Greater movement in the ankle joint could contribute to a greater CoP excursion which could also allow for more movement variability of the body to perform the dynamic task.

Total center of pressure excursion in the sagittal plane did not show significantly greater reach distance as compared to frontal plane movement. In order to complete a sagittal plane task, frontal plane movement variability displayed more significance in reach performance in this study. Control of balance in the frontal plane may be more required to perform a sagittal plane reach task to stabilize the body during movement variability.

This dichotomization of postural control strategy to differentiate single leg anterior reach performance, to our knowledge, as not been reported in literature. It is unknown the implications these postural control strategies on athletic performance.

3.11 Future Research

High stability is anticipated to indicate that the reach task is easy enough that the athlete does not need to use greater variability or center of pressure excursion in order to successfully complete the task. For the more stable athletes, the SLAR may simply not be challenging enough to require higher variability of motion, thus the SLAR test may be a false negative.

High variability indicates a possibly greater center of pressure excursion, but the ability to control and handle perturbations or increased changes in movement. It is expected that athletes with high variability would have a lower risk of injury compared to the athletes with high stability. The high variability population is anticipated to handle perturbations and changes in postural control more effectively, even though their CoP would have a higher excursion. Athletes with a high variability would not be statically balanced, but their dynamic balance would indicate a higher degree of control in competitive situations. Athletes who use a high variability postural control strategy may contract and recruit more muscles in order to accommodate for greater dynamic control. This indicates a greater degree of biomechanical stability and strength because more muscles in different compartments of the lower extremity are being contracted to maintain and manage perturbations.

These findings may have clinical implications for individuals demonstrating a lack of movement variability in the frontal plane resulting in lower sagittal plane reach distances. Improvements to frontal plane movement variability strategies may result in increased dynamic postural control.

Methods for the best interventions to improve dynamic postural control have yet to be determined by researchers and clinicians. Because specific postural control factors and variables have not been identified as the most important for intervention or assessment, it is difficult to objectively assess balance in regards to injury prevention or rehabilitation. Based off of the findings of this study, training postural control and stability in the frontal plane increases CoP excursion which in turn increases and improves balance. Training and rehabilitation programs for sports-related injuries should focus on specific aspects of neuromuscular and postural control in order to optimize balance.

3.12 Limitations

Several methodological techniques may be utilized to complete a SLAR test. Some athletes may use a slower, more constant velocity during a maximal reach while others may reach quickly to their maximum distance with a faster acceleration. Similar reach distance may be accomplished by different reach strategies, such as high stability or high variability of postural control. It is unknown if these strategic differences are related to lower extremity injury risk in athletes due to limited research in this area.

Determining the severity of an injury is a subjective matter and may pose as a limitation to this study. Variables such as CoP excursion has been proven to identify injuries but not severity of injuries because injury is not objectively defined.

Filtering the center of pressure position data was not taken into account for this study and could play a role in the center of pressure excursion calculations, especially since subjects were tested in two separate environments.

This study did not look at subject group differences when analyzing postural control strategy groups. For example, there was no analysis to see if a majority of the female or male subjects fell under the high or low excursion groups.

Figure 1

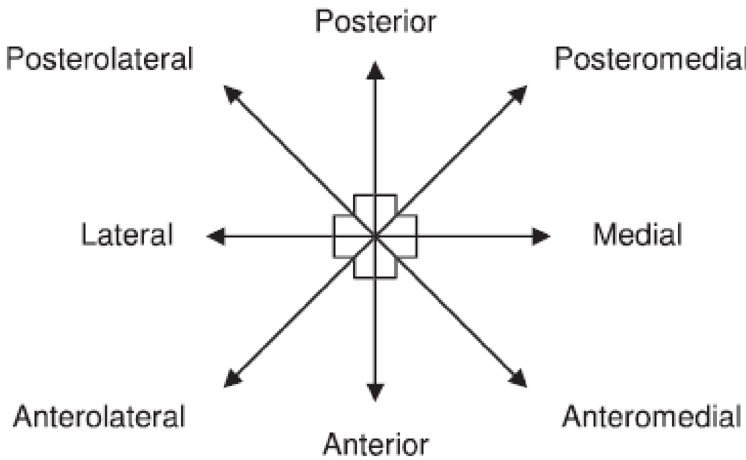

Figure 1: Star Excursion Balance Test reaching with the right leg[31]

Figure 2

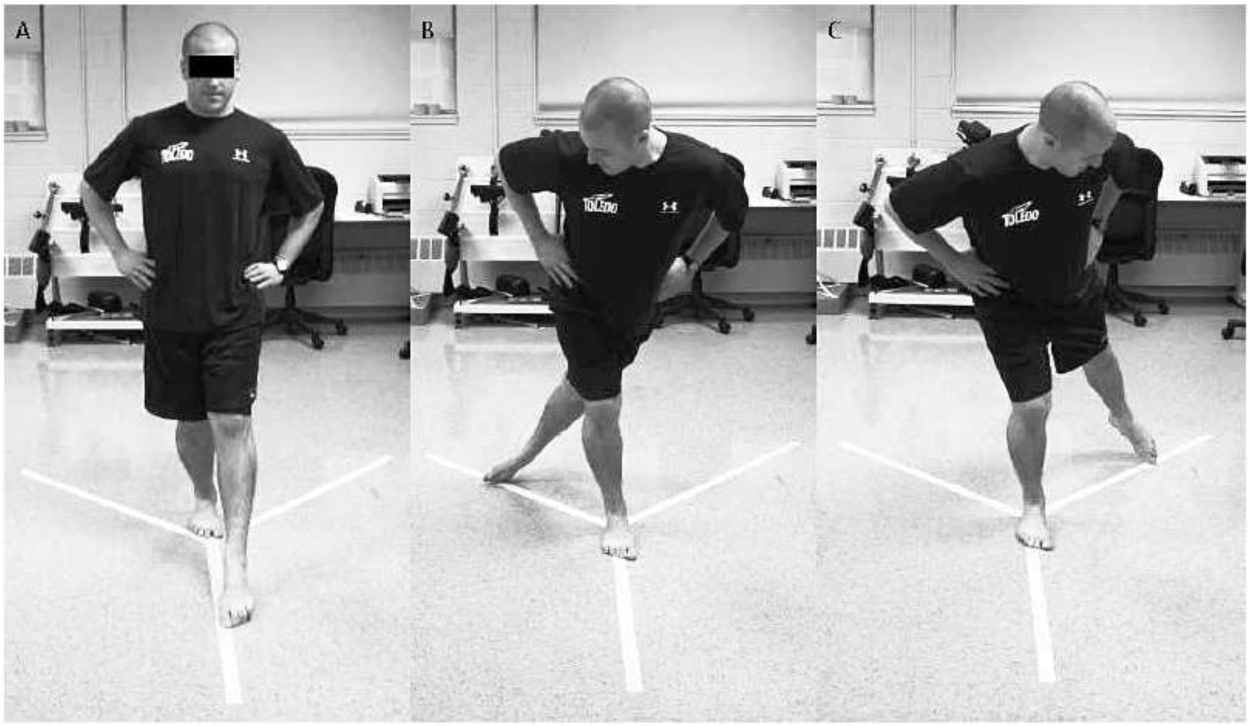

Figure 2: Y Balance Test – Lower Quarter in the (a) anterior direction, (b) posterolateral direction, and (c) posteromedial direction using the right leg as the stance leg.[31]

Figure 3

Figure 3: Single Leg Anterior Reach for the left leg as the stance limb

Figure 4

a. $$CoPx = \sum_{i=1}^{n} |x_{i+1} - x_i|$$

b. $$CoPy = \sum_{i=1}^{n} |y_{i+1} - y_i|$$

c. $$CoPtotal = \sum_{i=1}^{n} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$$

Figure 4: Center of pressure excursion in the (a) x axis, (b) y axis, and (c) total excursion

Figure 5

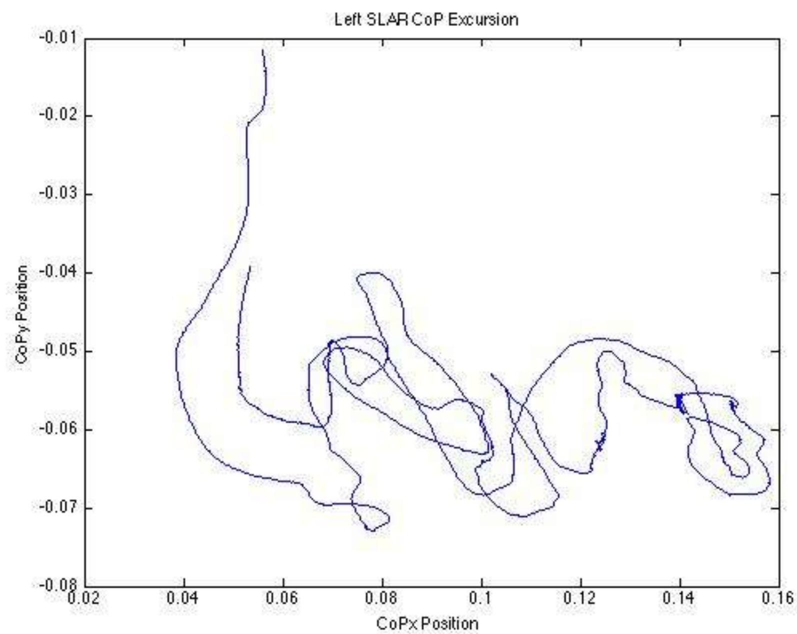

Figure 5: Matlab plot of center of pressure position data in the y axis versus the center of pressure position data in the x axis for a subject's left leg SLAR trial

Figure 6

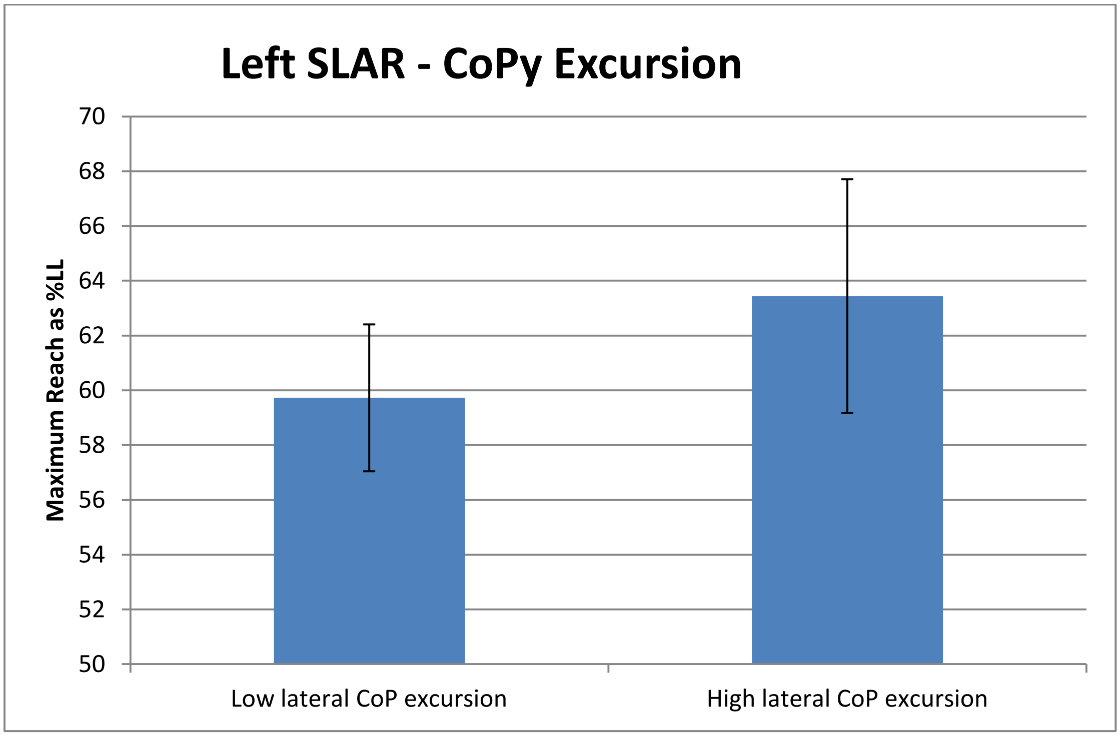

Figure 6: Left SLAR low maximum reach distance normalized to leg length (%LL) for low CoP excursion in the y axis (sagittal plane) and high CoP excursion in the y axis. No significance difference was found between groups.

Figure 7

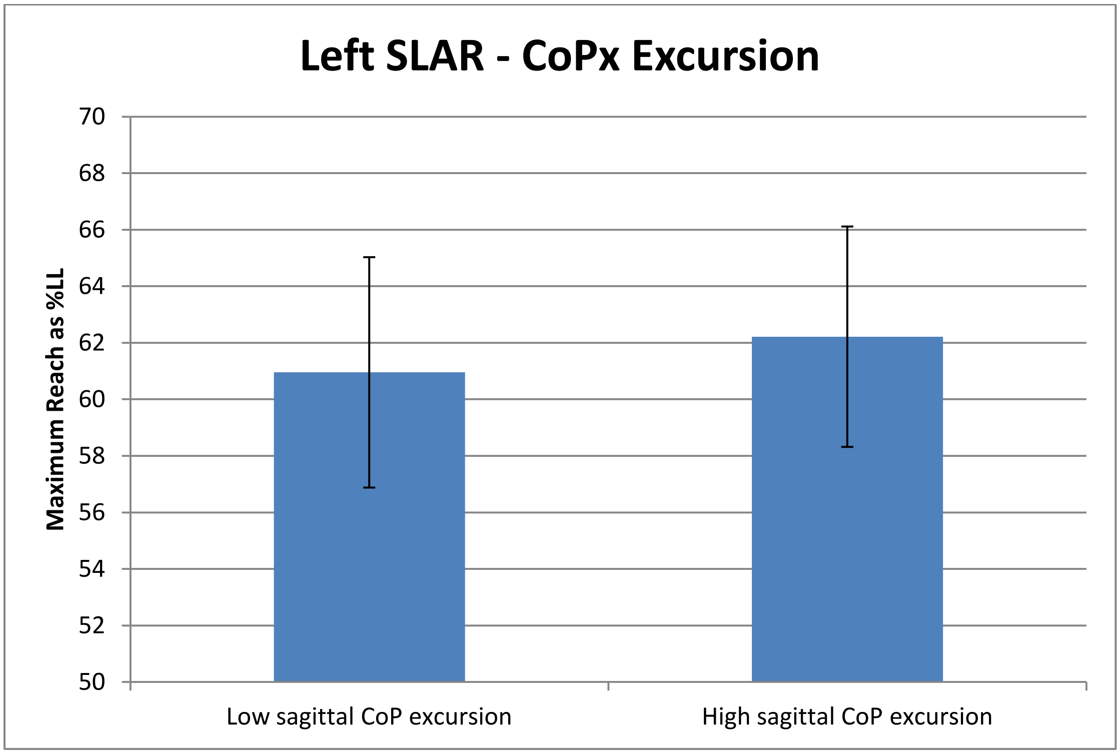

Figure 7: Left SLAR maximum reach distance normalized to leg length (%LL) for low CoP excursion in the x axis (frontal plane) and high CoP excursion in the x axis. Significant difference was found between groups at p<.05 level.

Figure 8

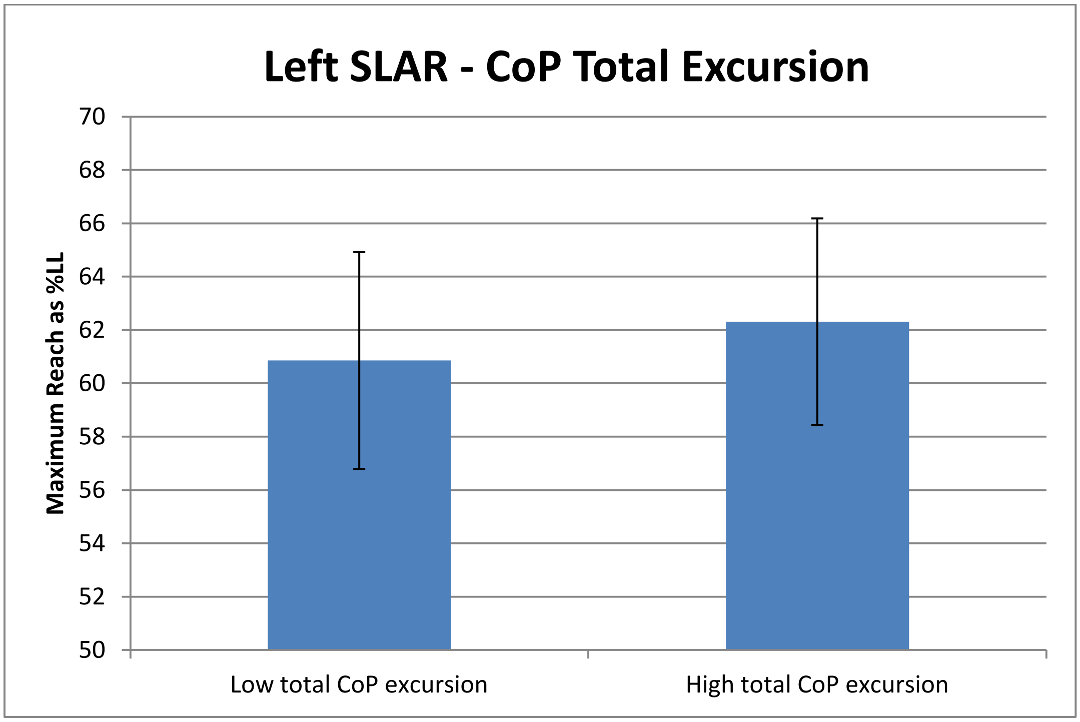

Figure 8: Left SLAR maximum reach distance normalized to leg length (%LL) for low CoP total excursion and high CoP total excursion. No significance difference was found between groups.

Figure 9

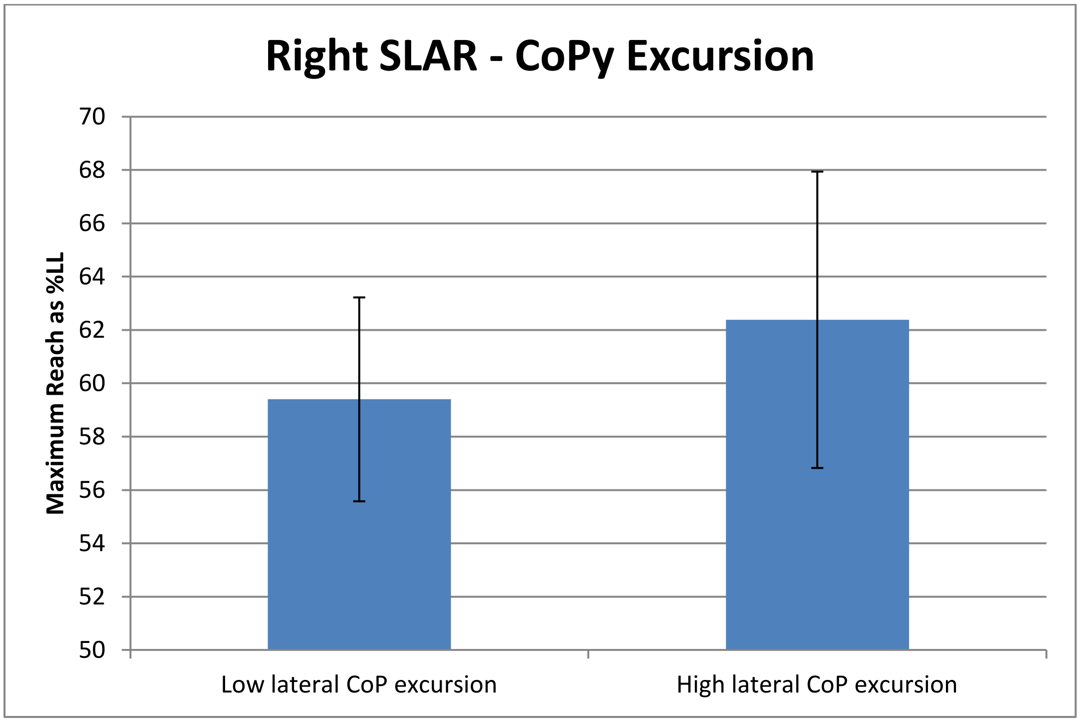

Figure 9: Right SLAR maximum reach distance normalized to leg length (%LL) for low CoP excursion in the y axis (sagittal plane) and high CoP excursion in the y axis. No significance difference was found between groups.

Figure 10

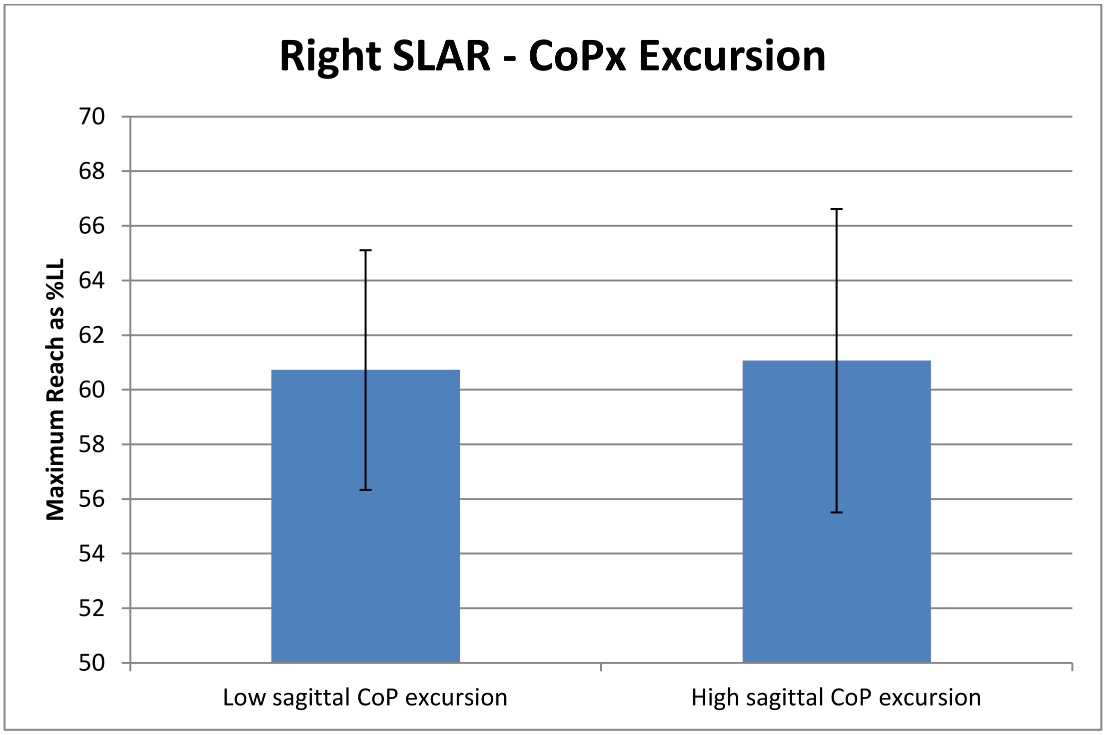

Figure 10: Right SLAR maximum reach distance normalized to leg length (%LL) for low CoP excursion in the x axis (frontal plane) and high CoP excursion in the x axis. Significant difference was found between groups at $p<.05$ level.

Figure 11

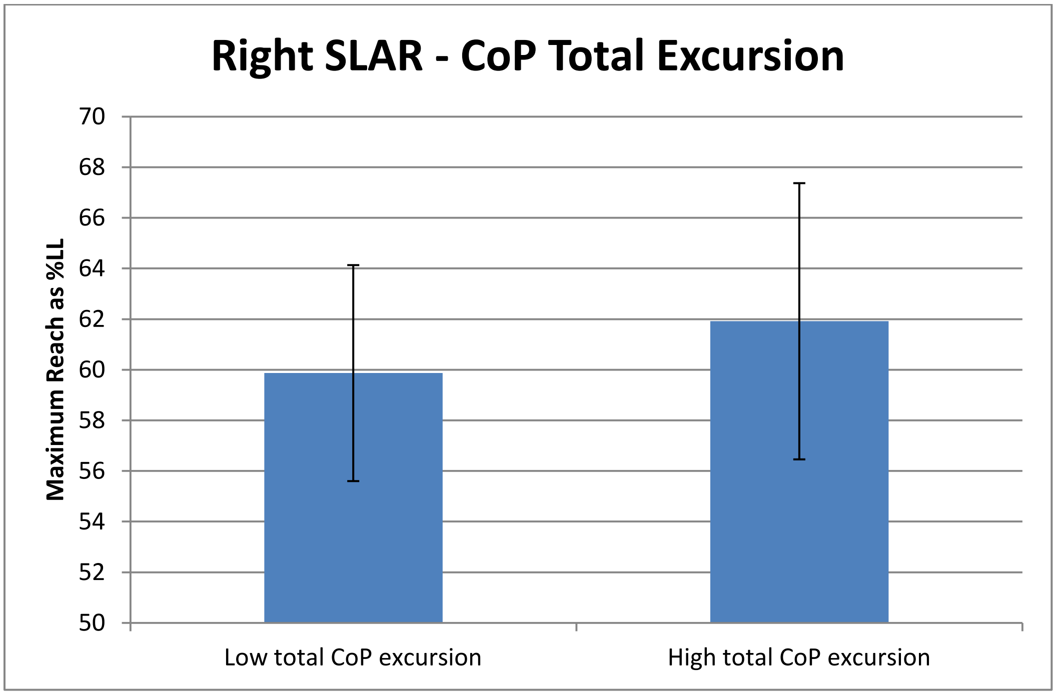

Figure 11: Right SLAR maximum reach distance normalized to leg length (%LL) for low CoP total excursion and high CoP total excursion. Significant difference was found between groups at p<.05 level.

Table 1

	CoP Excursion Component	Dichotomized Excursion (m)
Left Leg	CoPx	0.390
	CoPy	0.320
	CoPtotal	0.555
Right Leg	CoPx	0.380
	CoPy	0.314
	CoPtotal	0.548

Table 1: Center of pressure dichotomized excursion (50^{th} percentile excursion) for CoPx, CoPy, and CoPtotal for the left and right leg.

Table 2

	Normalized Mean Reach Distance (%LL)	**Standard Deviation**	**P-Value**
Low CoPy Excursion	59.7292	2.68	.300
High CoPy Excursion	63.4463	4.27	
Low CoPx Excursion	60.9567	4.07	.007
High CoPx Excursion	62.2188	3.90	
Low CoP Total Excursion	60.8590	4.07	.230
High CoP Total Excursion	62.3166	3.87	

Table 2: Left SLAR normalized mean reach distance (%LL) dichotomized for low and high center of pressure excursion in the x and y axis and total excursion

Table 3

	Normalized Mean Reach Distance (%LL)	Standard Deviation	P-Value
Low CoPy Excursion	59.4029	3.82	.822
High CoPy Excursion	62.3867	5.56	
Low CoPx Excursion	60.7238	4.39	.045
High CoPx Excursion	61.0657	5.55	
Low CoP Total Excursion	59.8711	4.27	.0173
High CoP Total Excursion	61.9185	5.46	

Table 3: Right SLAR normalized mean reach distance (%LL) dichotomized for low and high center of pressure excursion in the x and y axis and total excursion

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